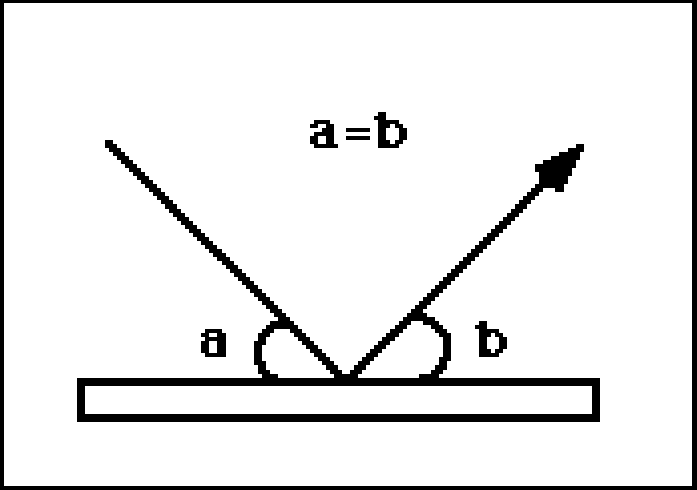

MECHANISM
WATER DROPLETS
Light and Optics
AIR, DUST,
ICE CRYSTALS

Reflection of Light

light bouncing off a surface

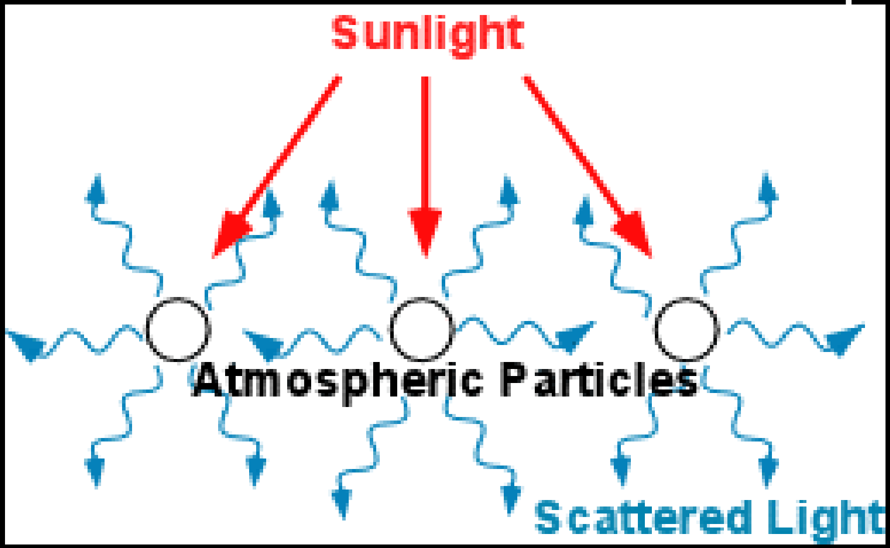
Light is said to be reflected when the angle at which light initially strikes a surface is equal to the angle at which light bounces off the same surface.



In the diagram above, light strikes a surface at an angle "a" and leaves at an angle "b" (relative to that surface). Because angle "a" is equal to angle "b", this is an example of reflected light.

Scattering of Light

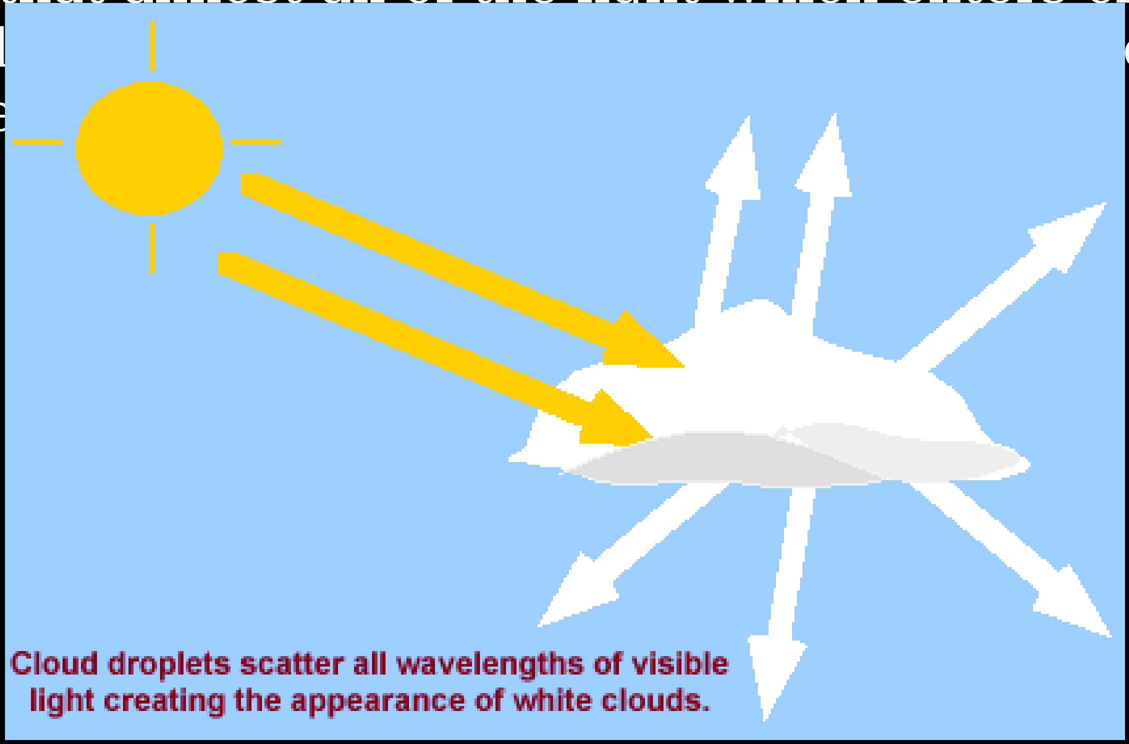
by small particles and molecules in the atmosphere



Different from reflection, where radiation is deflected in one direction, some particles and molecules found in the atmosphere have the ability to scatter solar radiation in all directions. The particles/molecules which scatter light are called scatterers and can also include particulates made by human industry.

Selective scattering (or Rayleigh scattering) occurs when certain particles are more effective at scattering a particular wavelength of light. Air molecules, like oxygen and nitrogen for example, are small in size and thus more effective at scattering shorter wavelengths of light (blue and violet). The selective scattering by air molecules is responsible for producing our blue skies on a clear sunny day.

Another type of scattering (called Mie Scattering) is responsible for the white appearance of clouds. Cloud droplets with a diameter of 20 micrometers or so are large enough to scatter all visible wavelengths more or less equally. This means that almost all of the light which enters clouds will be scattered clouds appear to be

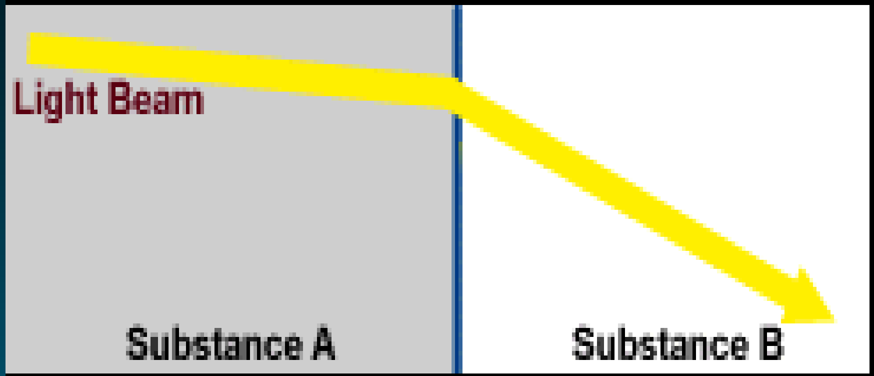


Cloud droplets scatter all wavelengths of visible light creating the appearance of white clouds.

When clouds become very deep, less and less of the incoming solar radiation makes it through to the bottom of the cloud, which gives these clouds a darker appearance.

Refraction of Light

as it passes from more dense to less dense mediums

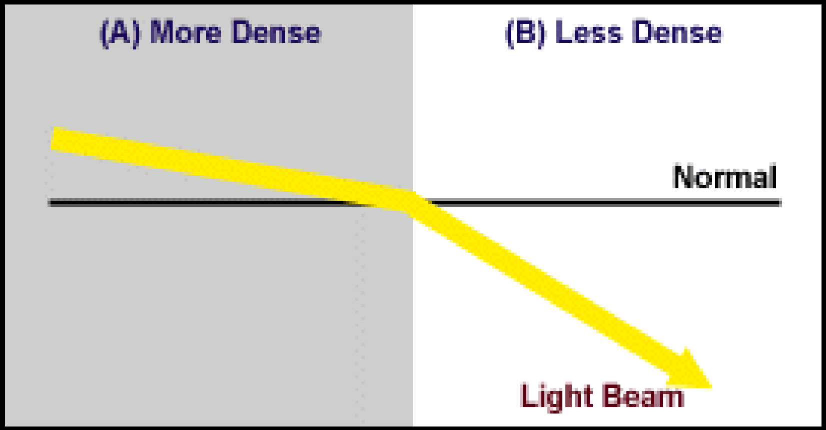


The bending of light as it passes from one medium to another is called refraction.

The angle and wavelength at which the light enters a substance and the density of that substance determine how much the light is refracted. The refraction of light by atmospheric particles can result in a number of beautiful optical effects like halos, which are produced when sunlight (or moonlight) is refracted by the pencil-shaped ice crystals of cirrostratus clouds.

When light passes from a more dense to a less dense substance, (for example passing from water into air), the light is refracted (or bent) away from the normal.

The normal is a line perpendicular (forming a 90 degree angle) to the boundary between the two substances. The bending occurs because light travels more slowly in a denser medium.



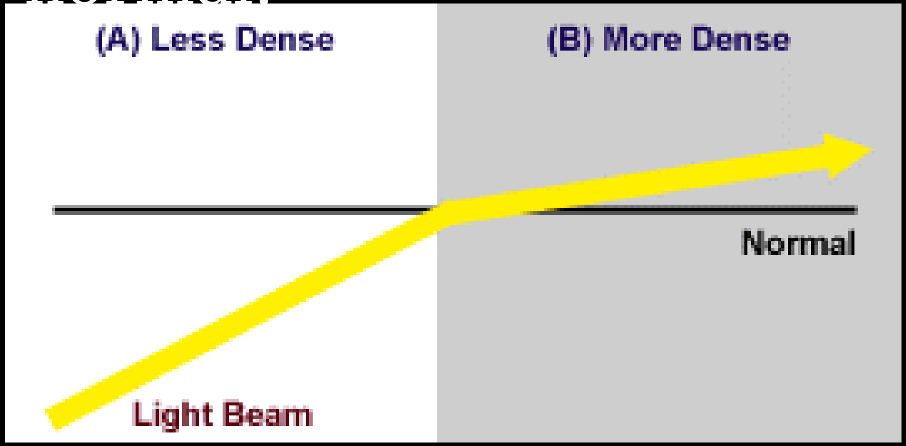
Another example of refraction is the dispersion of white light into its individual colors by a glass prism. As visible light exits the prism, it is refracted and separated into a magnificent display of colors.

Each color from the original beam of light has its own particular wavelength (or color) and each wavelength is slowed differently by the glass. The amount of refraction increases as the wavelength of light decreases. Shorter wavelengths of light (violet and blue) are slowed more and consequently experience more bending than do the longer wavelengths (orange and red).

Refraction of Light

as it passes from less dense to more dense mediums

When light passes from a less dense to a more dense substance, (for example passing from air into water), the light is refracted (or bent) towards the normal.



The normal is a line perpendicular (forming a 90 degree angle) to the boundary between the two substances. The bending occurs because light travels more slowly in a denser medium.

A demonstration of refraction can be conducted at home in a dark room. All that is needed is a flashlight, a clear glass filled with water and a small mirror.

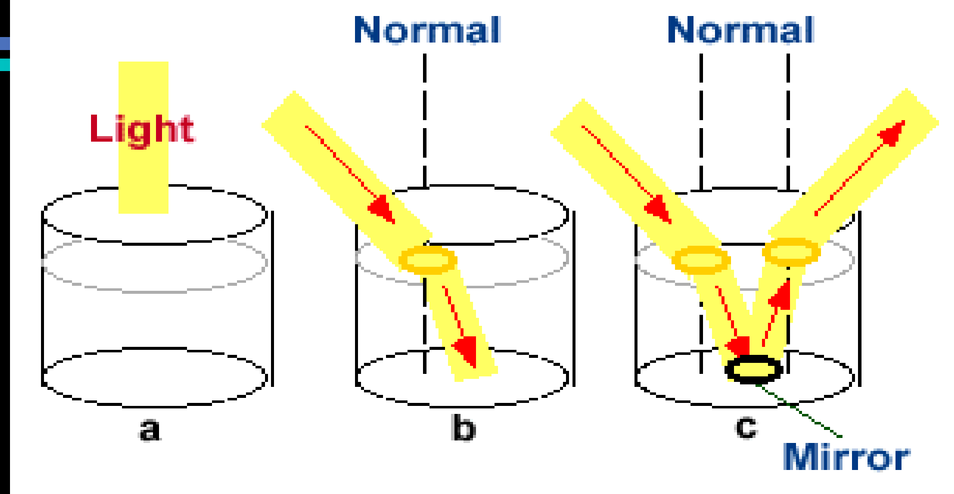


Figure (a): Shine the light directly into the glass. If the light strikes the water straight on (or parallel to the normal), no bending occurs and it simply passes directly into the water undisturbed, leaving only a straight beam of light all the way to the bottom of the glass.

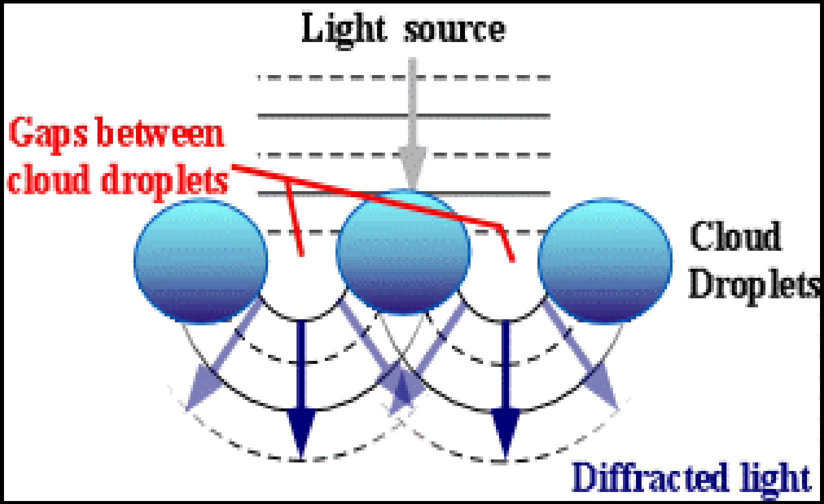
Figure (b): Shine the light into the glass at an angle. As the light enters the water, it is refracted. Since the light is passing from air (less dense) into water (more dense), it is bent towards the normal. The beam of light would appear to bend at the surface of the water.

Figure (c): Place a mirror at the bottom of the glass of water and again shine the light into the glass of water at an angle. As light initially enters the water, it is refracted as in figure (b) and then reflected off the mirror (at the bottom of the glass). Upon exiting the water, the light is bent away from the normal as it passes from water (more dense) and into air (less dense). The light would leave the flashlight, bend at the surface of the water, reflect off the mirror at the bottom of the glass and move towards the surface, where it would bend outward at the same angle it bent in on the way in.

Diffraction of Light

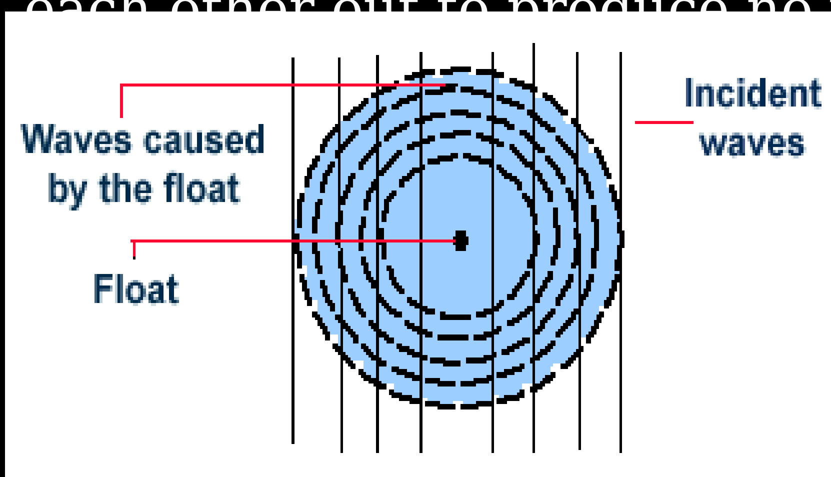
light bending around an object

Diffraction is the slight bending of light as it passes around the edge of an object. The amount of bending depends on the relative size of the wavelength of light to the size of the opening. If the opening is much larger than the light's wavelength, the bending will be almost unnoticeable. However, if the two are closer in size or equal, the amount of bending is considerable, and easily seen with the naked eye.



In the atmosphere, diffracted light is actually bent around atmospheric particles -- most commonly, the atmospheric particles are tiny water droplets found in clouds. Diffracted light can produce fringes of light, dark or colored bands. An optical effect that results from the diffraction of light is the silver lining sometimes found around the edges of clouds or coronas surrounding the sun or moon. The illustration above shows how light (from either the sun or

Optical effects resulting from diffraction are produced through the interference of light waves. To visualize this, imagine light waves as water waves. If water waves were incident upon a float residing on the water surface, the float would bounce up and down in response to the incident waves, producing waves of its own. As these waves spread outward in all directions from the float, they interact with other water waves. If the crests of two waves combine, an amplified wave is produced (constructive interference). However, if a crest of one wave and a trough of another wave combine, they cancel each other out to produce no vertical displacement

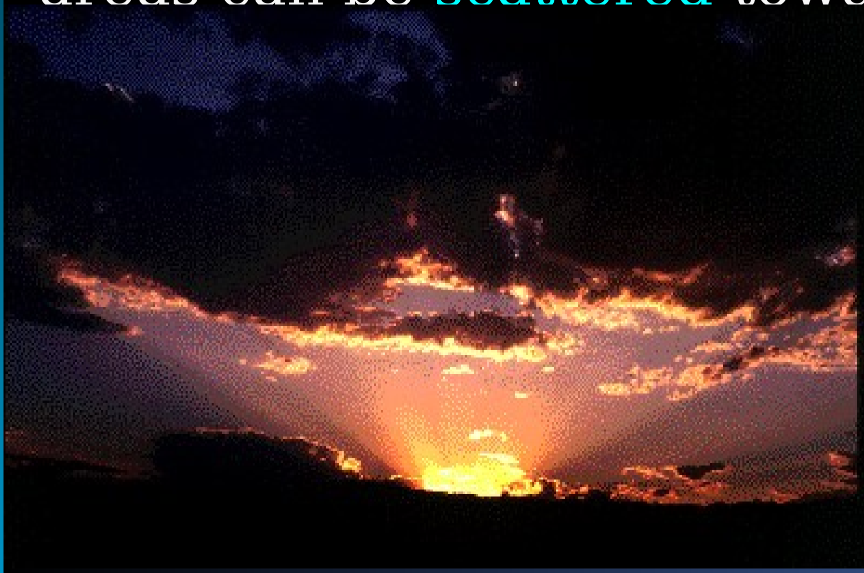


This concept also applies to light waves. When sunlight (or moonlight) encounters a cloud droplet, light waves are altered and interact with one another in a similar manner as the water waves described above. If there is constructive interference, (the crests of two light waves combining), the light will appear brighter. If there is destructive interference, (the trough of one

Crepuscular Rays

sun rays converging on the horizon

Crepuscular rays occur when objects such as mountain peaks or clouds partially shadow the sun's rays. The name crepuscular means "relating to twilight" and these rays are observed at sunrise and sunset. Crepuscular rays appear to diverge outward from the setting sun, and are visible only when the atmosphere contains enough haze or dust particles so that sunlight in unshadowed areas can be scattered toward the observer.



The light rays are actually parallel, but appear to converge to the sun due to "perspective", the same visual effect that makes parallel railroad tracks appear to converge in the distance. Crepuscular rays are often red or yellow in appearance because blue light from the

Light rays scattered by dust and haze occasionally appear to converge toward the "antisolar" point, (the location on the horizon opposite the point where the sun is setting). These rays, called anti-crepuscular rays, originate at the sun, cross over the sky to the opposite horizon, an isolar point becau

In the photo above, the sun is near the horizon behind the observer and sunlight is reflecting off the small cloud in the top right corner of the picture. Mountains and clouds behind the observer are responsible for the shadows in between.

Blue Skies and Blue Haze

resulting from selective scattering by air molecules

Blue skies are produced as shorter wavelengths of the incoming visible light (violet and blue) are selectively scattered by small molecules of oxygen and nitrogen -- which are much smaller than the wavelength of the light. The violet and blue light has been scattered over and over by the molecules all throughout the atmosphere, so our eyes register it as blue light c giving the sky its blue ap

Blue haze is a phenomenon commonly observed in the Smoky Mountains of eastern Tennessee and the Blue Ridge Mountains of Virginia.

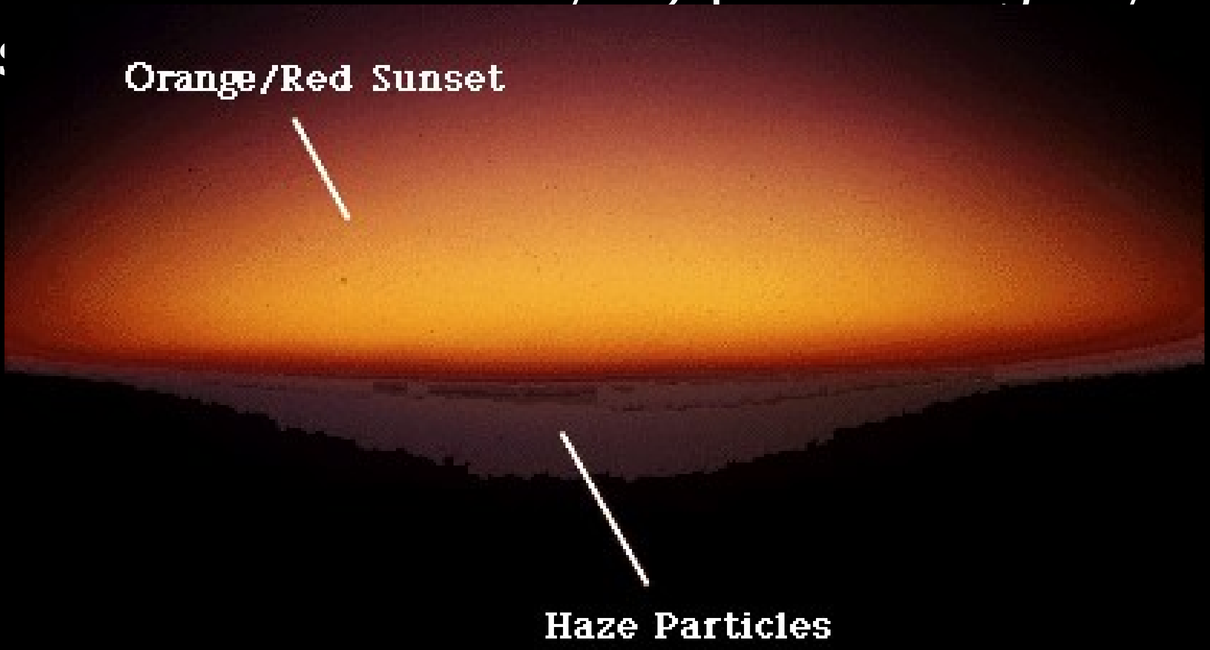
As tiny hydrocarbon particles released by vegetation chemically react with ozone molecules, they produce particles that selectively scatter blue light, giving the mountains their blue appearance.

Sunsets appear in a variety of colors

When the sun is high in the sky, it generally appears white because all wavelengths of visible light reach an observer's eyes with almost equal intensity. As the sun sinks toward the horizon, sunlight enters the atmosphere at a much lower angle and consequently must pass through much more atmosphere before being seen by an observer. Air molecules scatter away the shorter wavelengths of light (violet and blue) and the only light which penetrates through the atmosphere are the longer wavelengths of light (yellow, orange and red) which produce colorful sunsets. Because of the refraction of sunlight by the atmosphere itself, the sun will appear to be higher in the sky than it actually is. The combi[illegible] sunlight by atmospheric partic[illegible]ht, the brightness in the sky [illegible]low the horizon.

The size and concentration of atmospheric particles in the path of incoming sunlight determine the type of sunset observed. When sunlight encounters very few particles in the atmosphere, most wavelengths of light reach the observer's eyes with almost equal intensity. The reduced scattering produces the white or yellow sunsets commonly observed in the Rocky Mountains, where the atmosphere typically contains fewer dust and assorted part

As incoming sunlight passes through a more dense atmosphere, shorter wavelengths of light (violet and blue) are efficiently scattered away by particles suspended in the atmosphere. This allows predominantly yellow and red wavelengths of light to reach the observer's eyes, producing a yellowish-red sun



When there is a high concentration of particles in the atmosphere that are slightly larger than air molecules (like smoke, dust, and pollutants), shorter and intermediate wavelengths of light (violet, blue and yellow) are scattered away. Therefore, only the longer wavelengths (orange and red) reach th ange-red appearance.

When incoming sunlight encounters a heavy concentration of particles in the atmosphere, the shorter wavelengths of light (violet and blue) are scattered away, resulting in a red sunset. Red sunsets are often observed from a beach because of the high concentration of salt particles suspended in the air over the oceans. These particles effectively scatter shorter wavelengths of light, producing red sunsets. Dust and ash particles injected into the atmosphere by volcanic eruptions

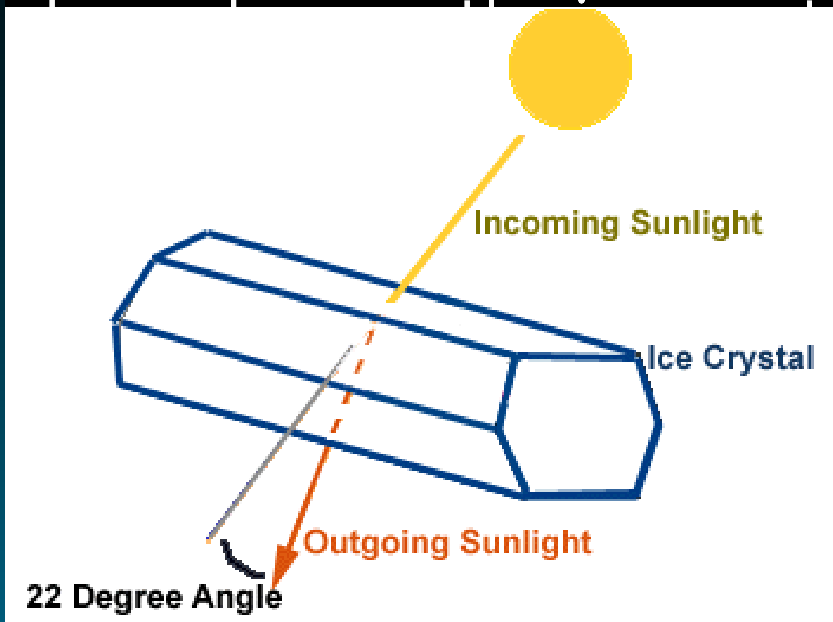
22 Degree Halo

a ring of light 22 degrees from the sun or moon

A halo is a ring of light surrounding the sun or moon. Most halos appear as bright white rings but in some instances, the dispersion of light as it passes through ice crystals found in upper level cirrus clouds can cause a halo to have color.

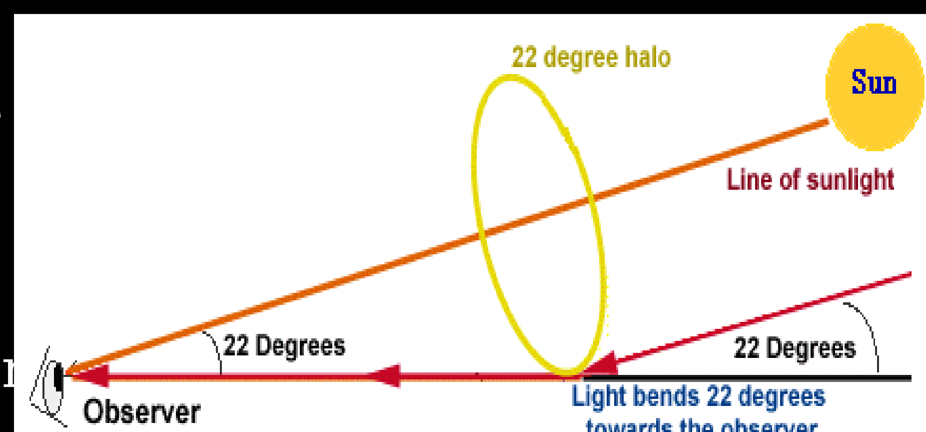
Halos form when light from the sun or moon is refracted by ice crystals associated with thin, high-level clouds (like cirrostratus clouds). A 22 degree halo is a ring of light 22 degrees from the sun (or moon) and is the most common type of halo observed and is formed by hexagonal ice crystals with diameters

Light undergoes two refractions as it passes through an ice crystal and the amount of bending that occurs ...al's diameter.



A 22 degree halo develops when light enters one side of a columnar ice crystal and exits through another side. The light is refracted when it enters the ice crystal and once again when it leaves the ice crystal.

The two refractions bend the light by 22 degrees from its original direction, producing ring of light observed at 22 degrees from the sun or moon



A tangent arc is a patch of bright light that is occasionally observed along a halo. This occurs when sunlight is refracted by falling hexagonal "pencil-shaped" ice crystals whose long axes are oriented horizontally.

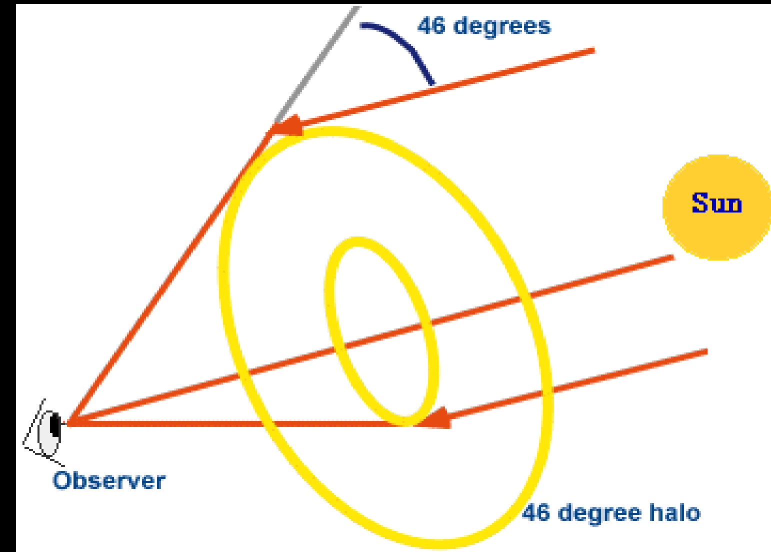
46 Degree Halo

a ring of light 46 degrees from the sun or moon

A 46 degree halo is a ring of light observed 46 degrees from the sun or moon. Although they are less common than 22 degree halos, the process by w milar.

What determines if a 46 degree halo or a 22 degree halo develops is the path of the light as it passes through hexagonal ice crystals. A 22 degree halo results from "in one side, out another side"; a 46 degree halo from "in one side, out the bottom".

The incoming light passes through ice crystals of thin, high-level clouds (like cirrostratus clouds) and is refracted by an angle of 46 degrees before being registered by the eye. Consequently, an observer sees a ring of light around the sun (or moon) at an



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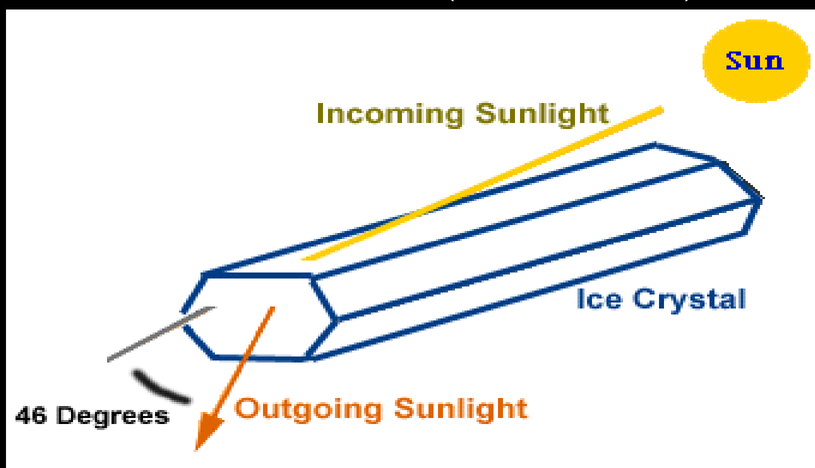


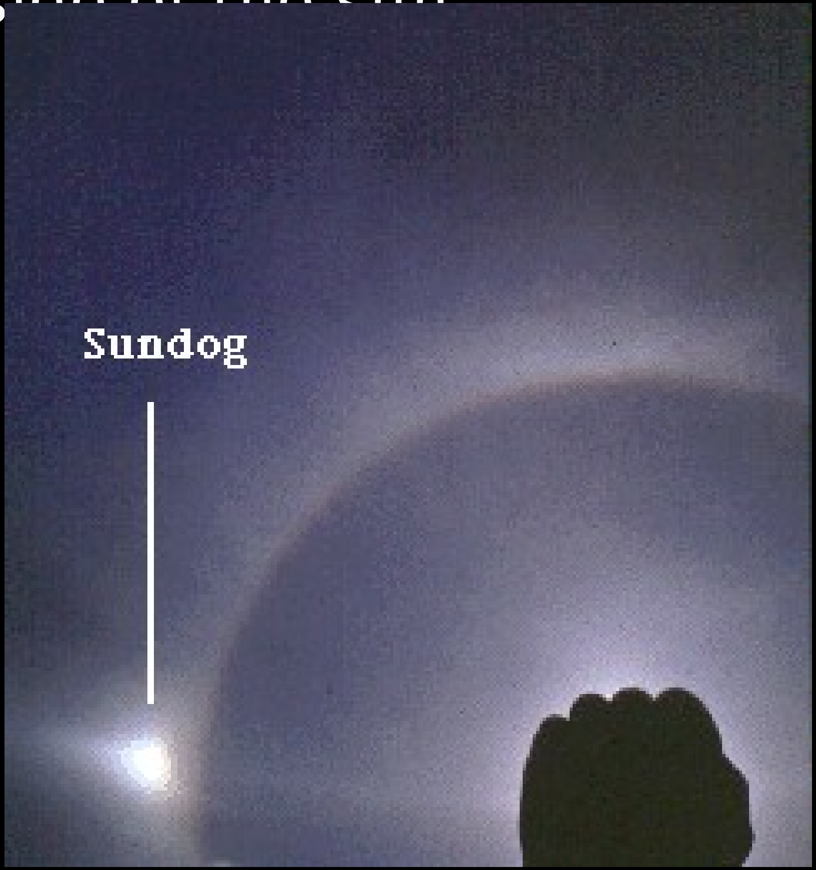
These ice crystals are hexagonal-shaped columns with diameters between 15 and 25 micrometers and have an appearance resembling tiny pencils.

A 46 degree halo develops when light enters one side of a columnar ice crystal and exits from either the top or bottom face of the crystal. The light is refracted twice as it passes through the ice crystal and the two refractions bend the light by 46 degrees from its original direction. This bending produces a ring of light observed at 46 degrees from the sun or moon.

Sundogs

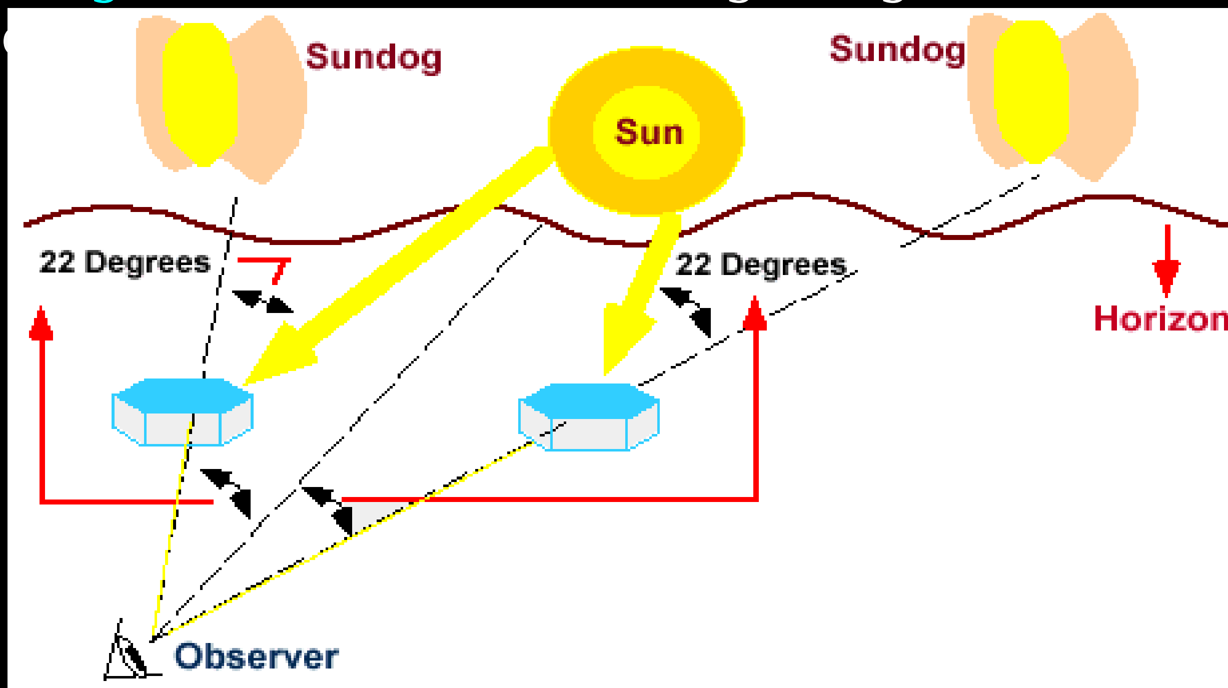
mock suns or parhelia

Sundogs, also known as mock suns or "parhelia", are a pair of brightly colored spots, one on either side of the sun.



Sundogs form as sunlight is refracted by hexagonal plate-like ice crystals with diameters larger than 30 micrometers and their flat faces horizontally oriented.

Sundogs are visible when the sun is near the horizon and on the same horizontal plane as the observer and the ice crystals. As sunlight passes through the ice crystals, it is bent by 22 degrees before reaching our eyes, much like what happens with 22 degree halos. This bending of light results in the formati



The difference between sundogs and halos is the preferential orientation of the ice crystals through which the light passes before reaching our eyes. If the hexagonal crystals are oriented with their flat faces horizontal, a sundog is observed. If the hexagonal crystals are randomly oriented, a halo is

Sun Pillars

vertical shafts of light

A sun pillar is a vertical shaft of light extending upward or downward from the sun. Typically seen during sunrise or sunset, sun pillars form when sunlight reflects off the surfaces of falling ice crystals associated with thin, high-level clouds (like cirrostratu

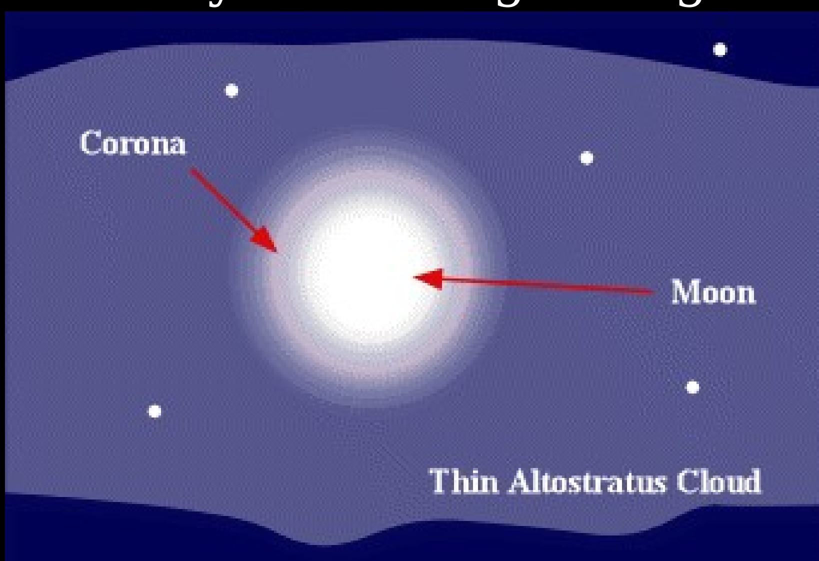
The hexagonal plate-like ice crystals fall with a horizontal orientation, gently rocking from side to side as they fall.

When the sun is low on the horizon, an area of brightness appears in the sky above (or below) the sun as sunlight is reflected off the surfaces of these tipped ice crystals.

Coron as

produced by diffraction of light

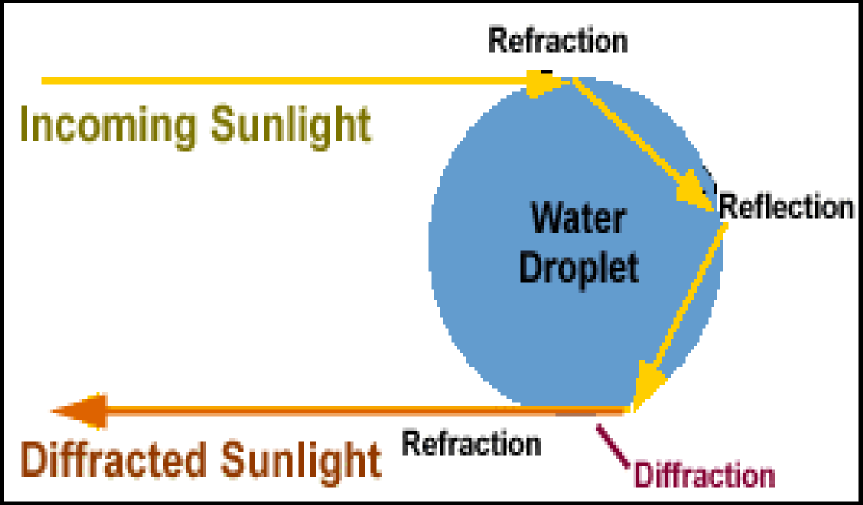
When the distance between the drops is similar to the wavelength of visible light, the light that shines through the cloud droplets is diffracted and dispersed in the manner shown below. On a clear night, for example, the light you see coming from the moon is coning straight from the moon. However if a thin cloud layer is found between the observer and the moon, the diffraction and dispersion of the moonlight actually casts a light larger than the original light source. This n[...]on is called the corona.



When the cloud droplets are very uniform in size, the diffracted light can cause the corona to be separated into its component colors, with blue light to the inside of the red light. These colors may repeat themselves, surrounding the moon with a series of colored rings, becoming fainter as each

Also, a combination of refraction, reflection and diffraction can combine to produce other optical effects such as glories and the "Heiligenschein" effect -- which is a bright area around the head of an observer's shadow on a surface containing spherical water droplets. Glories are the rings of illuminated light seen most commonly from plane's shadows as they fly over clouds of liquid water. In both phenomena, the light ultimately is bent close to 180° right back to the observer.

As a beam of light encounters a water droplet, it is refracted as it enters the droplet. Portions of the light are then internally reflected off the backside of the droplet. Before the light exits the droplet completely, it diffracts along the droplet's outer surface for just an instant as a surface wave before refracting as it



Silver Lining and Cloud Iridescence

produced through diffraction of sunlight

In the picture below, the sun is shining from behind the growing cumulus tower. This bright outline along the edge of the cloud is the silver lining, which occurs when light is diffracted by cloud droplets along the cloud's outer edge. Silver linings are g larger droplets.

Sometimes, diffraction of sunlight in clouds produce a multitude of colors. This optical effect is called cloud iridescence.

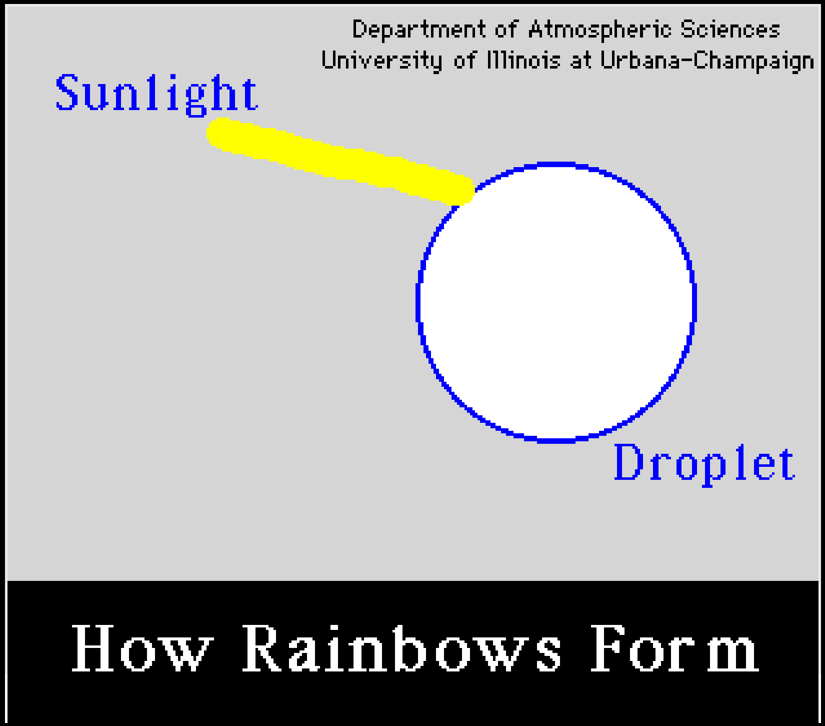
These colors are usually observed within 20 degrees of the sun and are easier to look at through sunglasses.

Rainbows

an arc of concentric
bands

A rainbow is an arc of concentric colored bands that develops when sunlight interacts with rain drops.

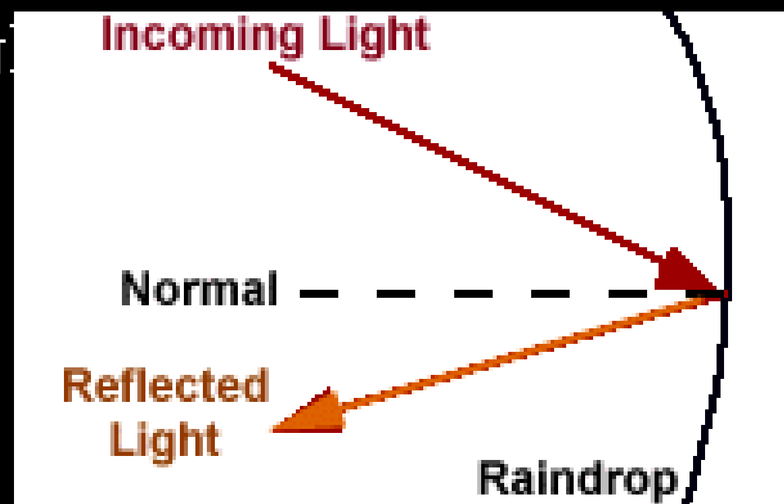
A rainbow occurs when rain is falling in one portion of the sky and the sun is shining in another. For a rainbow to be seen, the sun must be behind an observer who is facing falling rain.



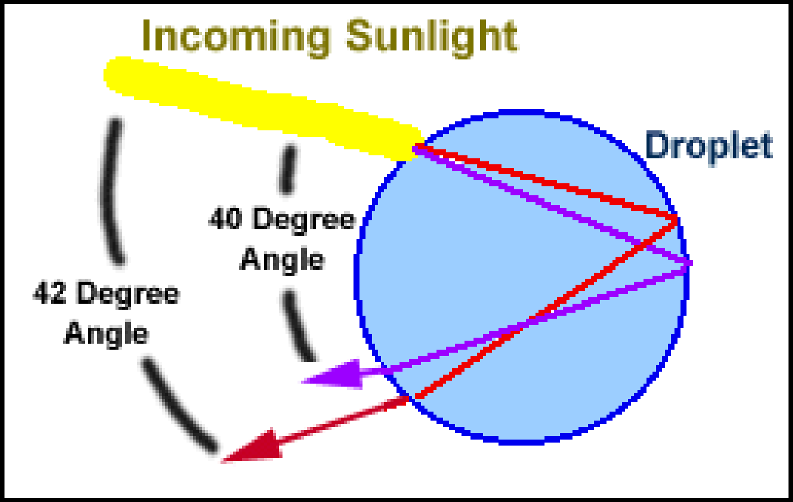
Sunlight is refracted as it enters a raindrop, which causes the different wavelengths (colors) of visible light to separate. Longer wavelengths of light (red) are bent the least while shorter wavelengths (violet) are bent the most.

If the angle between the refracted light and the normal to the drop surface is greater than a critical angle, the light reflects off the back of the drop.

The critical angle for water (which would apply to raindrops) is 48 degrees (relative to the normal). Therefore, if light strikes the back of a raindrop at an angle greater than 48 degrees, it will be reflected back. If the angle is smaller than 48 degrees, the lig
will simply pass on through.



The reflected light is refracted as it exits the drop. Violet light (bending the most) emerges at an angle of 40 degrees relative to the incoming sunlight while red light (bending the least) exits the drop at an angle of 42 degrees. Other colors of the rainbow leave a raindrop at angles somewhere in between. According to Descartes' calculations using laws of optics, the three stage refraction-reflection-refraction pattern that light undergoes when passing through a raindrop produces a concentration of outgoing rays along a line that is 42 degrees above the head of an observer's shadow. This concentration of light rays is the rainbow that we see.



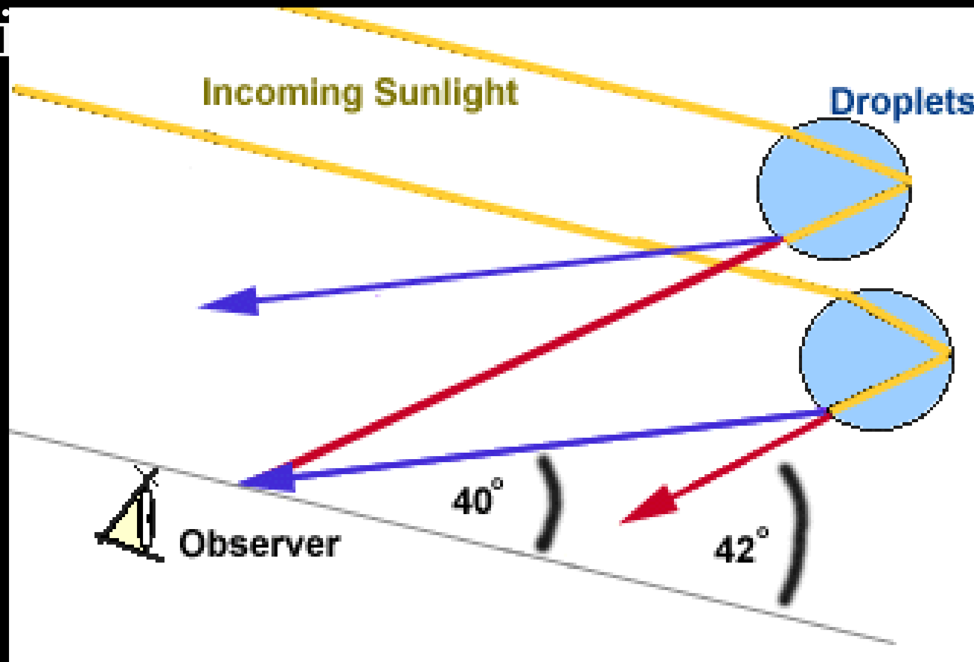
Since only one color of light is observed from each raindrop, an incredible number of raindrops is required to produce the magnificent spectrum of colors that are characteristic of a rainbow.

Primary Rainbows

brighter than a secondary rainbow

A primary rainbow is brighter than a secondary rainbow and has colors changing from red on the outside to violet on the inside.

We will focus on two raindrops to explain why this color pattern develops. Red light from the higher drop is directed toward the observer's eyes, while violet light i [illegible] e observer.



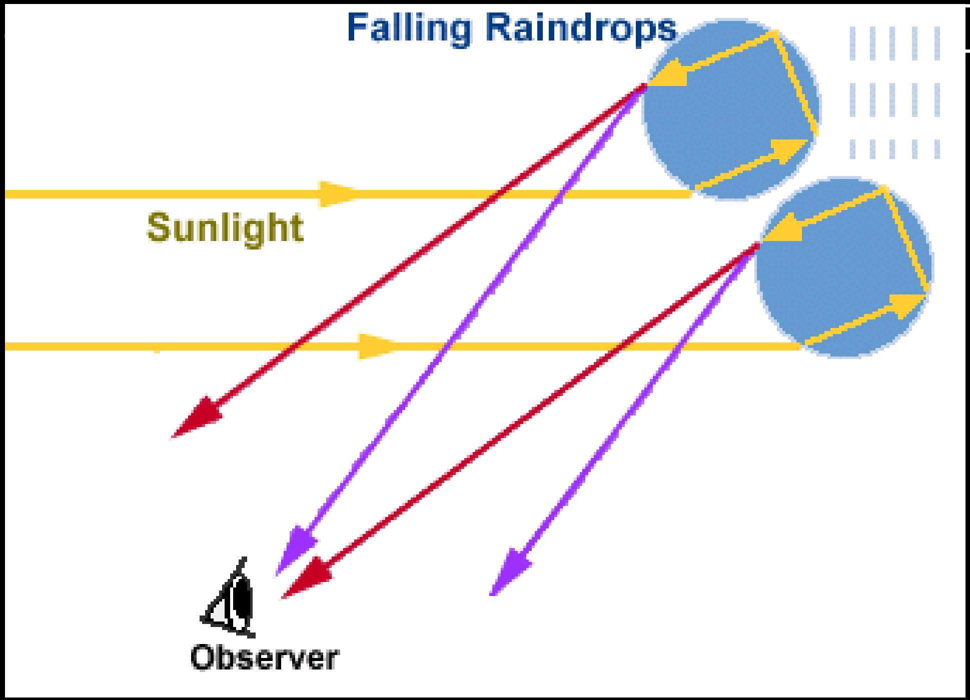
From the lower drop, red light is directed to a level below the line of sight, while violet light is seen by the observer. This is why the colors of a primary rainbow change from red on the top of the arc to violet on the bottom.

Secondary Rainbows

fainter than a primary rainbow

A secondary rainbow appears outside of a primary rainbow and develops when light entering a raindrop undergoes two internal reflections instead of just one (as is the case with a primary rainbow). The intensity of light is reduced even further by the second reflection, so secondary rainbows are not as bright as primary rainbows. Alternatively: fewer light rays go th … step sequence

The color scheme of the secondary rainbow is opposite of the primary rainbow. Violet light from the higher drop enters the observer's eye, while red light from th here.



Simultaneously, red light from the lower drop enters the observer's eye and violet light is not seen. This is why the colors of a secondary rainbow change from violet on the top to red on the bottom.